Azimuthal Asymmetry of Prompt Photons in Nuclear Collisions

B. Z. Kopeliovich[1,2], A. H. Rezaeian[1] and Iván Schmidt[1]

[1] *Departamento de Física y Centro de Estudios Subatómicos, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile*
[2] *Joint Institute for Nuclear Research, Dubna, Russia*

Abstract

The azimuthal elliptic asymmetry v2 observed in heavy ion collisions, is usually associated with properties of the medium created in the final state. We compute the azimuthal asymmetry which is due to multiple interactions of partons at the initial stage of nuclear collisions, and which is also present in pA collisions. In our approach the main source of azimuthal asymmetry is the combination of parton multiple interactions with the steep variation of the nuclear density at the edge of nuclei. We apply the light-cone dipole formalism to compute the azimuthal asymmetry of prompt photons yield from parton-nucleus, proton-nucleus and nucleus-nucleus collisions at the RHIC energy.

PACS:13.85.QK, 24.85.+p, 13.60.Hb, 13.85.Lg
Keywords: Relativistic Heavy Ion collisions, Direct photons, Azimuthal asymmetry

1 Introduction

Prompt photons, i.e. photons not from hadronic decays, are interesting since they do not participate in the strong interactions and therefore carry information about the initial state hard collisions. Nevertheless, measuring prompt photons is a challenge for experimentalists, partly due to the existence of large backgrounds coming from hadronic decays, which should be extracted. Even after this subtraction, there are other several sources for direct photons, including thermal radiation from the hot medium and photons induced by final state interactions with the medium. In this paper we concentrate on the azimuthal asymmetry of prompt photons produced at the initial stage of relativistic nuclear collisions.

The PHENIX collaboration at RHIC has recently reported in Refs. [1,2] the measurement of an azimuthal asymmetry of direct photon production, which has been studied recently in several theoretical papers [3,4,5,6]. A novel mechanism which produces an azimuthal asymmetry coming from the reaction's initial conditions was introduced in Ref. [3]. This is in contrast with the usual assumptions taken in approaches where the azimuthal asymmetry is only associated with the properties of the medium created in the final state. We show that at least part of the direct photon azimuthal asymmetry, albeit small for AA and pA collisions, originates from initial hard scatterings between partons of the nuclei. In our approach, the main source of the azimuthal asymmetry originates from the sensitivity of parton multiple interactions to the steep variation of the nuclear density at the edge of the nuclei, which correlates with the color dipole orientation.

This paper is organized as follows: In sections 2 and 3 we introduce the main formalism for prompt photon production and discuss the relevance of color dipole orientation. In section 4, we introduce the azimuthal asymmetry for various collisions. In section 5, we present the numerical results. Some concluding remarks are given in section 6.

2 Photon radiation in the color dipole formalism

The transverse momentum (p_T) distribution of photon bremsstrahlung, coming from the interaction of a quark with nuclear matter of thickness $T_A(b) = \int_{-\infty}^{\infty} dz \rho_A(z,b)$ (where the nuclear density ρ_A is integrated along the parton trajectory at impact parameter b), integrated over the final quark transverse momentum can be written as [3,7],

$$\frac{d\sigma^{qA}(q\to q\gamma)}{d(ln\alpha)d^2\vec{p}_T d^2\vec{b}} = \frac{1}{(2\pi)^2}\sum_{in,f}\int d^2\vec{r}_1 d^2\vec{r}_2 e^{i\vec{p}_T\cdot(\vec{r}_1-\vec{r}_2)}\phi^{\star}_{\gamma q}(\alpha,\vec{r}_1)\phi_{\gamma q}(\alpha,\vec{r}_2) \times F_A(\vec{b},\alpha\vec{r}_1,\alpha\vec{r}_2,x), \tag{1}$$

where α denotes the fraction of the quark light-cone momentum carried by the photon, and $\phi_{\gamma q}(\alpha,\vec{r})$ is the light-cone amplitude for the $q\gamma$ fluctuation with transverse separation $\vec{r}$. In this equation the QCD part is encoded in the function $F_A(\vec{b},\alpha\vec{r}_1,\alpha\vec{r}_2,x)$, which is a linear combination of $\bar{q}q$ dipole partial amplitudes on a nucleus at impact parameter $\vec{b}$,

$$F_A(\vec{b},\alpha\vec{r}_1,\alpha\vec{r}_2,x) = \mathrm{Im} f^A_{q\bar{q}}(\vec{b},\alpha\vec{r}_1,x) + \mathrm{Im} f^A_{q\bar{q}}(\vec{b},\alpha\vec{r}_2,x) - \mathrm{Im} f^A_{q\bar{q}}(\vec{b},\alpha(\vec{r}_1-\vec{r}_2),x), \tag{2}$$

where the partial elastic amplitude $f^A_{q\bar{q}}$ can be written, in the eikonal form, in terms of the dipole elastic amplitude $f^N_{q\bar{q}}$ of a $\bar{q}q$ dipole colliding with a proton at impact parameter $\vec{b}$ [8],

$$\begin{aligned}\mathrm{Im} f^A_{q\bar{q}}(b,\vec{r}) &= 1-\left[1-\frac{1}{A}\int d^2\vec{s}\ \mathrm{Im} f^N_{q\bar{q}}(\vec{s},\vec{r})T_A(\vec{b}+\vec{s})\right]^A \\ &\approx 1-\exp[-\int d^2\vec{s}\ \mathrm{Im} f^N_{q\bar{q}}(\vec{s},\vec{r})T_A(\vec{b}+\vec{s})].\end{aligned} \tag{3}$$

Dependence on the light-cone momentum fraction x of the target gluons and α are implicit in the above expression. The dipole partial elastic amplitude $f^N_{q\bar{q}}$ was proposed in Ref. [3] to have the form

$$\begin{aligned}\mathrm{Im} f^N_{q\bar{q}}(\vec{s},\vec{r}) &= \frac{1}{12\pi}\int\frac{d^2\vec{q}}{q^2}\frac{d^2\vec{q}'}{q'^2}e^{i\vec{s}.(\vec{q}-\vec{q}')}\alpha_s\mathcal{F}(x,\vec{q},\vec{q}')\left(e^{-i\vec{q}\cdot\vec{r}\eta}-e^{i\vec{q}\cdot\vec{r}(1-\eta)}\right) \\ &\times\left(e^{i\vec{q}'\cdot\vec{r}\eta}-e^{-i\vec{q}'\cdot\vec{r}(1-\eta)}\right),\end{aligned} \tag{4}$$

where we defined $\alpha_s=\sqrt{\alpha_s(q^2)\alpha_s(q'^2)}$. The fractional light-cone momenta of the quark and antiquark are denoted by η and $1-\eta$, respectively. The radiated photon takes away fraction α of the quark momentum. Therefore, we have the parameter $\eta=1/(2-\alpha)$ for the photon production. It is known that the center of gravity of $q\bar{q}$ is closer to fastest q or $\bar{q}$. The generalized unintegrated gluon density [1] $\mathcal{F}(x,\vec{q},\vec{q}')$ is related to the diagonal one by $\mathcal{F}(x,q)=\mathcal{F}(x,\vec{q},\vec{q}=\vec{q}')$. Integrating over the vector $\vec{s}$ one can recover the dipole cross section $\sigma^N_{q\bar{q}}(r)$, and also η or α dependence will disappear

$$\begin{aligned}\sigma^N_{q\bar{q}}(r) &= 2\int d^2\vec{s}\ \mathrm{Im} f^N_{q\bar{q}}(\vec{s},\vec{r}) \\ &= \frac{4\pi}{3}\int\frac{d^2q}{q^4}(1-e^{-i\vec{q}.\vec{r}})\alpha_s(q^2)\mathcal{F}(x,q).\end{aligned} \tag{5}$$

Relying on the saturation shape of the dipole cross-section $\sigma^N_{q\bar{q}}(r)$ [10], the following form for $\alpha_s\mathcal{F}(x,\vec{q},\vec{q}')$ was proposed in Ref. [3],

$$\alpha_s\mathcal{F}(x,\vec{q},\vec{q}')=\frac{3\sigma_0}{16\pi^2}q^2q'^2R_0^2(x)e^{-\frac{1}{8}R_0^2(x)\left(q^2+q'^2\right)}e^{-\frac{1}{2}R_N^2(\vec{q}-\vec{q}')^2}, \tag{6}$$

where the parameters $\sigma_0=23.03$ mb, $R_0(x)=0.4\mathrm{fm}\times(x/x_0)^{0.144}$ with $x_0=3.04\times10^{-4}$ are fixed to HERA data for the proton structure function [10]. The

[1] This should not be mixed up with the generalized gluon density [9] which is off-diagonal in the longitudinal fractional momentum x.

parameter $R_N^2 = 5$ GeV^{-2} is the t-slope of the pomeron-proton vertex [3]. The energy scale x which enters in the dipole amplitude is related to the measurable variable $x = p_T/w$ [11], where w is the center of mass energy. Unfortunately, it is not possible to uniquely determine the unintegrated gluon density function from the available data. Nevertheless, the proposed form Eq. (6) seems to be a natural generalization which preserves the saturation properties of the diagonal part [3]. After carrying out the integrations in Eq. (4) the dipole amplitude gets the following simple form,

$$\begin{aligned}\mathrm{Im} f_{q\bar{q}}^N(\vec{s},\vec{r}) = \frac{\sigma_0}{8\pi B_{el}} \Bigg\{ \exp\left[-\frac{[\vec{s}+\vec{r}(1-\eta)]^2}{2B_{el}}\right] + \exp\left[-\frac{(\vec{s}-\vec{r}\eta)^2}{2B_{el}}\right] \\ - 2\exp\left[-\frac{r^2}{R_0^2(x)} - \frac{[\vec{s}+(1/2-\eta)\vec{r}]^2}{2B_{el}}\right]\Bigg\}, \qquad (7)\end{aligned}$$

where we defined $B_{el} = R_N^2 + R_0^2(x)/8$.

In Eq. (1), $\phi_{\gamma q}(\alpha,\vec{r})$ is the light-cone (LC) distribution amplitude of the projectile quark γq fluctuation. Averaging over the initial quark polarizations and summing over all final polarization states of the quark and photon, we get

$$\begin{aligned}\sum_{in,f} \phi^\star_{\gamma q}(\alpha,\vec{r}_1)\phi_{\gamma q}(\alpha,\vec{r}_2) = \frac{\alpha_{em}}{2\pi^2} m_q^2 \alpha^2 \{\alpha^2 K_0(\alpha m_q r_1) K_0(\alpha m_q r_2) \\ + [1+(1-\alpha)^2] \frac{\vec{r}_1.\vec{r}_2}{r_1 r_2} K_1(\alpha m_q r_1) K_1(\alpha m_q r_2)\}, \qquad (8)\end{aligned}$$

where $K_{0,1}(x)$ denotes a modified Bessel function of the second kind and m_q is an effective quark mass, which can be conceived as a cutoff regularization. We take $m_q = 0.2$ GeV for the case of direct photon production [11]. It has been also shown that a value of $m_q = 0.2$ GeV is needed in order to describe nuclear shadowing effects [12].

Expression (1), with the exponentials expanded to first order in the nuclear thickness, provides also the cross-section for direct photon production in hadron-hadron collision. We have recently shown that in this framework one can obtain a good description of the cross section for prompt photon production data for proton-proton (pp) collisions at RHIC and Tevatron energies [11]. Predictions for the LHC in the same framework are given in Ref. [13], while to compare with the predictions of other approaches at the LHC see Ref. [14].

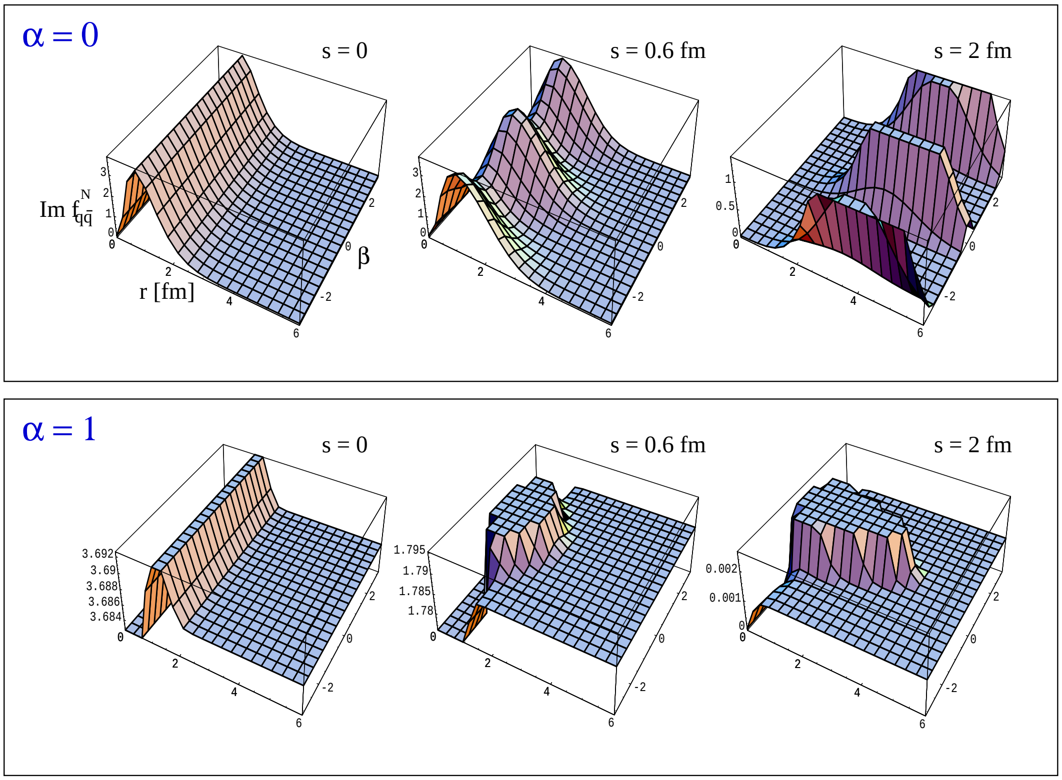

Fig. 1. The partial elastic amplitude Im$f^N_{q\bar{q}}$ (mb) of the $\bar{q}q$ dipole on a proton at impact parameter s as a function of dipole size r and angle β defined between $\vec{s}$ and $\vec{r}$ for two values of $\alpha = 0, 1$. We use a fixed value of $x = 0.01$ for all plots.

3 Azimuthal asymmetry and dipole orientation

The main source of azimuthal asymmetry in the amplitude (3) is the interplay between multiple rescatering and the shape of the physical system. The key function which describes the effect of multiple interactions is the eikonal exponential in Eq. (3), while the information about the shape of the system is incorporated through a convolution of the impact parameter dependent partial elastic amplitude and the nuclear thickness function. Notice that the initial space-time asymmetry gets translated into a momentum space anisotropy by the double Fourier transform in Eq. (1).

It is quite obvious intuitively that although the Rutherford scattering cross section is azimuthally symmetric, the azimuthal angle of the radiated photons transverse momentum at a given impact parameter $\vec{s}$ correlates with the direction of $\vec{s}$. In terms of the partial elastic amplitude $f^N_{q\bar{q}}(\vec{s}, \vec{r})$, it means that the vectors $\vec{r}$ and $\vec{s}$ are correlated. This is the key observation which leads to an azimuthal asymmetry in pA and AA collisions.

In Fig. (1) we show the partial dipole amplitude $f^N_{q\bar{q}}(\vec{s}, \vec{r})$ as a function of the dipole size r and the angle β between $\vec{s}$ and $\vec{r}$, at various fixed values of s for

two values of $\alpha = 0, 1$. Notice that the generic feature of the partial dipole amplitude, e. g. its maximum and minimum pattern, changes with α. One can see that for very small dipole size r the dipole orientation is not important. For very large dipole size r compared to the impact parameter s or very small values of s the dipole orientation is also not present. Notice, however, that it is not obvious a priori how the convolution between the partial dipole amplitude and the nuclear profile, which leads to a more complicated angle mixing, gives rise to a final azimuthal asymmetry. The main aim of this paper is to calculate such azimuthal asymmetry without using any approximations.

4 Azimuthal asymmetry in qA, pA and AA collisions

The azimuthal asymmetry of prompt photon production, resulting from parton-nucleus (qA) collisions, is defined as the second order Fourier coefficients in a Fourier expansion of the azimuthal dependence of a single-particle spectra Eq. (1) around the beam direction,

$$v_2^{qA}(p_T, b, \alpha) = \frac{\int_{-\pi}^{\pi} d\phi \cos(2\phi) \frac{d\sigma^{qA}(q\to q\gamma)}{d(ln\alpha)d^2\vec{p}_T d^2\vec{b}}}{\int_{-\pi}^{\pi} d\phi \frac{d\sigma^{qA}(q\to q\gamma)}{d(ln\alpha)d^2\vec{p}_T d^2\vec{b}}}, \tag{9}$$

where the angle ϕ is defined with respect to the reaction plane. Some of integrals in the above expression can be analytically performed. After some tedious but straightforward calculation one obtains

$$v_2^{qA}(p_T, b, \alpha) = \frac{\int_0^\infty drr\Psi_N(p_T, r, \alpha)\Phi_N(b, r, \alpha)}{\int_0^\infty drr\Psi_D(p_T, r, \alpha)\Phi_D(b, r, \alpha) + 2\pi\mathcal{N}(\alpha, p_T)}, \tag{10}$$

where the functions Ψ_D and Ψ_N, which contain information about γq fluctuation, are defined by

$$
\begin{aligned}
\Psi_N(p_T,r,\alpha) = & \frac{\alpha_{em}}{2\pi^2}\{2m_q^2\alpha^4\left(-\frac{J_2(p_tr)K_0(\alpha m_q r)}{p_T^2+(\alpha m_q)^2}+\frac{r}{4\alpha m_q}J_2(p_tr)K_1(\alpha m_q r)\right)\\
& + [1+(1-\alpha)^2]\Big(\frac{\alpha m_q p_T}{p_T^2+(\alpha m_q)^2}\left(J_1(p_tr)-J_3(p_tr)\right)K_1(\alpha m_q r)\\
& + J_2(p_tr)K_0(\alpha m_q r)-\frac{r\alpha m_q}{2}J_2(p_tr)K_1(\alpha m_q r)\Big)\};\\
\Psi_D(p_T,r,\alpha) = & \frac{\alpha_{em}}{2\pi^2}\{2m_q^2\alpha^4\left(-\frac{J_0(p_tr)K_0(\alpha m_q r)}{p_T^2+(\alpha m_q)^2}+\frac{r}{4\epsilon}J_0(p_tr)K_1(\alpha m_q r)\right)\\
& + [1+(1-\alpha)^2]\Big(-\frac{2\alpha m_q p_T}{p_T^2+(\alpha m_q)^2}J_1(p_tr)K_1(\alpha m_q r)\\
& + J_0(p_tr)K_0(\alpha m_q r)-\frac{r\alpha m_q}{2}J_0(p_tr)K_1(\alpha m_q r)\Big)\};\\
\mathcal{N}(\alpha,p_T) = & \frac{\alpha_{em}}{2\pi^2}\left(\frac{m_q^2\alpha^4}{(p_T^2+(\alpha m_q)^2)^2}+\frac{(1+(1-\alpha)^2)p_T^2}{(p_T^2+(\alpha m_q)^2)^2}\right),
\end{aligned}
\tag{11}
$$

where $J_n(x)$ $,n=0-3$ denotes the Bessel functions of the first kind. The functions $\Phi_{N,D}(b,r,\alpha)$ in Eq. (10) contain information about the QCD part and also the shape of the nucleus;

$$
\begin{aligned}
\Phi_N(b,r,\alpha) = & -\int_{-\pi}^{\pi} d\beta e^{-\int d^2\vec{s}\ \mathrm{Im}f_{q\bar{q}}^N(\vec{s},\alpha\vec{r})T_A(\vec{b}+\vec{s})}\cos(2\beta),\\
\Phi_D(b,r,\alpha) = & \int_{-\pi}^{\pi} d\beta e^{-\int d^2\vec{s}\ \mathrm{Im}f_{q\bar{q}}^N(\vec{s},\alpha\vec{r})T_A(\vec{b}+\vec{s})},
\end{aligned}
\tag{12}
$$

where β is the angle between $\vec{b}$ and $\vec{r}$, and the dipole amplitude $f_{q\bar{q}}^N(\vec{s},\vec{r},)$ was defined in Eq. (7). It is interesting to note that in the final form of v_2^{qA}, Eq. (10), the angle ϕ between the impact parameter $\vec{b}$ and the transverse momentum of the projectile quark $\vec{p}_T$ disappeared, and then the azimuthal asymmetry is directly related to the dipole orientation with respect to the impact parameter $\vec{b}$ through the angle β (see Eq. (12)). Therefore, if one neglects the dipole orientation the azimuthal asymmetry becomes identically zero, regardless of both the nuclear profile and the dipole cross-section parametrization.

In order to obtain the hadronic cross section from the elementary partonic cross section Eq. (1), we use the standard convolution based on QCD factorization [15],

$$
\frac{d\sigma^{\gamma}(pA\to\gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}} = \frac{1}{x_1+x_2}\int_{x_1}^1\frac{d\alpha}{\alpha}F_2^p(\frac{x_1}{\alpha},p_T)\frac{d\sigma^{qA}(q\to q\gamma)}{d(ln\alpha)d^2\vec{p}_T d^2\vec{b}}. \tag{13}
$$

We take the parametrization for the proton structure function $F_2^p(x,Q^2)$ given in Ref. [16]. Here x_1 denotes the fraction of the light-cone momentum of the

projectile hadron carried away by the photon, and we define $x_2 = x_1 - x_F$, where $x_F = 2p_L/\sqrt{\mathbf{s}}$ is the Feynman variable. The azimuthal asymmetry of photon yield in proton-nucleus (pA) interactions is then defined as

$$v_2^{pA}(b, p_T) = \frac{\int_{-\pi}^{\pi} d\phi \cos(2\phi) \frac{d\sigma^{\gamma}(pA \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}}}{\int_{-\pi}^{\pi} d\phi \frac{d\sigma^{\gamma}(pA \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}}}, \tag{14}$$

The above equation can be also simplified to an expression similar to Eq. (10), but now augmented with the proton structure function and an extra integral over the variable α.

The spectra of photon bremsstrahlung from nucleus-nucleus (AA) collisions can be obtained from Eq. (13) by weighting the cross-section with the density overlap factor of nuclei. In principle, one may obtain the cross-section for AA collisions in the same fashion as was done in Eq. (13) for the case of pA collisions, that is by making a convolution with the nucleus structure function instead of the proton structure function. However, the medium modification of nucleon structure function for the range of p_T values we are interested in is less than 20% [18] and therefore will not change the overall prediction. The azimuthal asymmetry of photon yield from collisions of two nucleus A_1 and A_2 at impact parameter B is defined as

$$\begin{aligned}
v_2^{A_1 A_2}(B, p_T) &= \frac{\int_{-\pi}^{\pi} d\phi \cos(2\phi)\ \mathcal{G}_N}{\int_{-\pi}^{\pi} d\phi\ \mathcal{G}_D}; \\
\mathcal{G}_N &= \int d^2\vec{b} \cos(2\Theta_1) \frac{d\sigma^{\gamma}(pA_1 \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_1} T_{A_2}(\vec{b}_2) \\
&\quad + \int d^2\vec{b} \cos(2\Theta_2) \frac{d\sigma^{\gamma}(pA_2 \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_2} T_{A_1}(\vec{b}_1); \\
\mathcal{G}_D &= \int d^2\vec{b} \left(\frac{d\sigma^{\gamma}(pA_1 \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_1} T_{A_2}(\vec{b}_2) + \frac{d\sigma^{\gamma}(pA_2 \to \gamma X)}{dx_F d^2\vec{p}_T d^2\vec{b}_2} T_{A_1}(\vec{b}_1) \right),
\end{aligned} \tag{15}$$

where we used the notation $\vec{b}_2 = \vec{b} + \vec{B}$, $\vec{b}_1 = \vec{b}$ ($\vec{b}$ is the impact parameter of the pA_1 collision) and the angle Θ_1 (Θ_2) is the angle between the vectors $\vec{b}_1$($\vec{b}_2$) and $\vec{B}$, respectively. The factor $\cos(2\Theta_{1,2})$ in the above equation relates the reaction planes of the pA and the AA collisions. The integral over $\vec{b}$ in Eq. (15) covers the almond shape area of the nucleus-nucleus overlap.

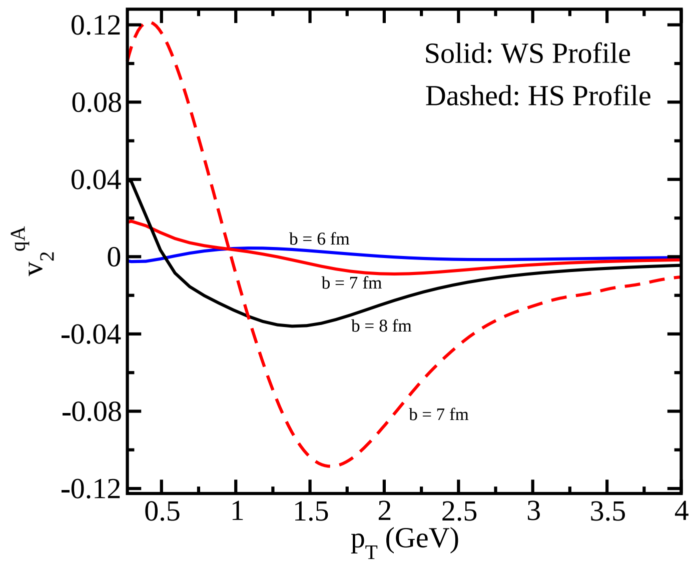

Fig. 2. The azimuthal anisotropy of prompt photon production coming from quark-nucleus collisions, at various impact parameter b and at the RHIC energy, for both the Woods-Saxon (WS) and hard sphere (HS) profiles. The relative fraction of the quark momentum carried by photon is taken to be $\alpha = 1$ for all curves.

5 Numerical result and discussions

We will perform a numerical calculation for the RHIC energy $\sqrt{\mathbf{s}} = 200$ GeV, at midrapidities. The only external input is the nuclear profile. First, we take a popular Woods-Saxon (WS) profile, with a nuclear radius $R_A = 6.5$ fm and a surface thickness $\xi = 0.54$ fm, for Pb+Pb collisions [17].

In Fig. (2) we show the calculated values of v_2^{qA} defined in Eq. (9), for fixed $\alpha = 1$, at various qA collision impact parameters b, and at the RHIC energy. For central collisions, the correlation between nuclear profile and dipole orientation is minimal. In fact, if the nuclear profile function was constant, then the convolution between the nuclear profile and the dipole orientation, defined in Eq. (3), would be trivial, and v_2^{qA} becomes then identically zero. Therefore, the main source of azimuthal anisotropy is not present for central collisions. This can be seen in Fig. (2), where a pronounced elliptic anisotropy is observed for collisions with impact parameters close to the nuclear radius R_A, where the nuclear profile undergoes rapid changes. Therefore, an important parameter which controls the elliptic asymmetry in this mechanism is $|b - R_A|$. We have verified this numerically by taking different R_A values for the WS profile, but with the same surface thickness ξ.

In Fig. (3) we show v_2^{pA} for prompt photons produced in non-central pA collisions, for the WS nuclear profile. Notice that at very small transverse momentum our results are not reliable, because the employed proton structure function is not valid.

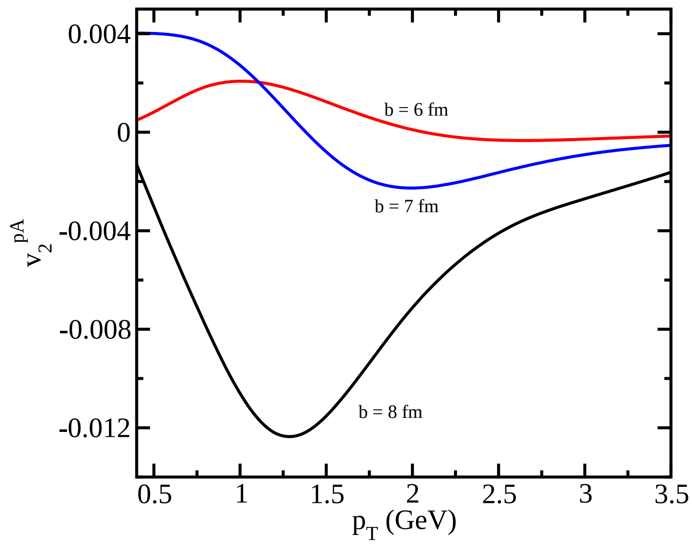

Fig. 3. The impact parameter dependence of prompt photon azimuthal asymmetry for proton-nucleus collisions at various impact parameter b at RHIC energy. For the nuclear profile, we have taken the Woods-Saxon (WS) profile for all curves.

In Fig. (4) we show the prompt photon azimuthal asymmetry for AA collisions defined in Eq. (15), at various impact parameters and at RHIC energy. The absolute value of v_2^{AA} turns out to be reduced compared to both v_2^{pA} and v_2^{qA}. The reason is that the integrand in Eq. (15) gets contributions only from semi-peripheral pA collisions where our mechanism is at work, and most of the integral over $\vec{b}$ does not contribute. This significantly dilutes the signal. For prompt photon, there is no suppression mechanism related to medium effects, as for the case of hadron production in central AA collisions compared to pp collisions [19]. For hadronic v_2, the inclusion of such suppression effects significantly enhances the azimuthal asymmetry coming from this mechanism [20]. The other diluting factor for v_2^{AA} is the presence of an extra $\cos(2\Theta)$ in Eq. (15), which accounts for the changing of the reaction plane going from pA to AA collisions. At high p_T, where the dipole size is very small, the dipole orientation becomes less important and consequently the correlation between the dipole cross-section and the nuclear profile disappears, i.e. the azimuthal asymmetry vanishes. This can be seen from Figs. (2,3,4), where v_2 for all qA, pA and AA collisions approaches to zero at high p_T.

In our approach the profile of nuclear density at the edge is a very important input, since the elliptic asymmetry stems from the rapid change of nuclear density at the edge. In order to show this more clearly and to estimate the theoretical uncertainty of our calculations, we obtain the elliptic asymmetry for the hard sphere profile with a constant density distribution, $\rho_A = \rho_0 \Theta(R_A - r)$, with the same nuclear radius R_A as the WS profile for Pb. In Fig. (2) we show the azimuthal asymmetry v_2^{qA} for the hard sphere profile (HS) at impact parameter $b = 7$ fm. For the HS profile the nuclear thickness changes at nuclear radius more steeply compared to the WS profile and consequently the elliptic

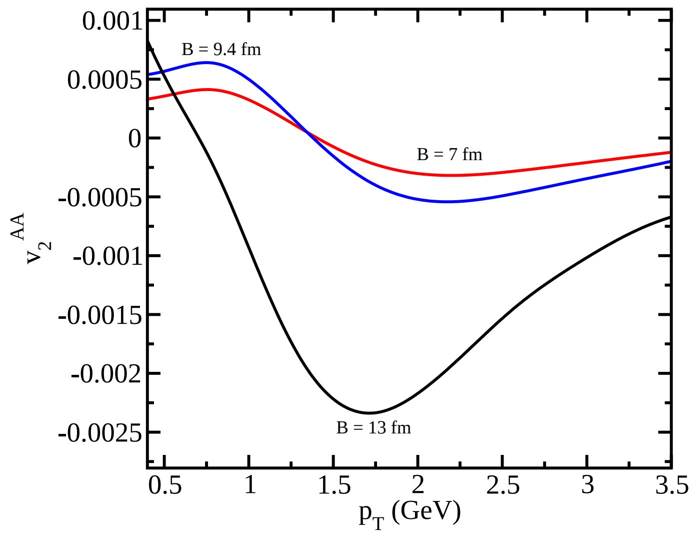

Fig. 4. The impact parameter B dependence of prompt photon azimuthal asymmetry, for Pb+Pb collisions at RHIC energy, with the WS nuclear profile.

asymmetry is significantly bigger. Notice that at impact parameter $b = 7$ fm for the HS profile, even though there is no matter, the correlation between color dipole and the variation of nuclear thickness still exists and consequently the azimuthal asymmetry is not zero.

6 Summary and final remarks

We have computed the azimuthal asymmetry of prompt photons originating from primary hard scatterings between partons. This can be accounted for by the inclusion of the color dipole orientation, which is sensitive to the rapid variation of the nuclear profile. We showed that the azimuthal asymmetry v_2 coming from this mechanism changes the sign and becomes negative for peripheral collisions, albeit it is extremely small. The first experimental attempts by PHENIX to extract the elliptic flow of direct photons yielded results which are compatible with zero within error bars [1]. However, the data was still contaminated with background from hadron decays. Recently, the PHENIX collaboration has presented preliminary data on v_2 of direct photons [2]. Although the systematics errors are still very large, the data indicates that v_2 of direct photons is larger than our prediction for v_2 of prompt photons. Therefore, if data is confirmed, other sources for v_2 of direct photons should be also important.

There are, however, a number of caveats in our approach which need further study before taking the numbers predicted here at face value. As we have shown, the tail of nuclear profile is an important external input in this mechanism and quite significantly affects the results. For example, we showed that

the azimuthal asymmetry is enhanced almost by an order of magnitude for the HS nuclear profile compared to the WS one (see Fig. (2)). Unfortunately the tail of all available nuclear profile parametrizations is less reliable, since it is not well probed by electron scattering and is obtained by a simple extrapolation. This is also due to the fact that the neutron distribution, which may be more important on the periphery, cannot be properly accounted for by electron scattering data. This brings uncertainty to our results. Furthermore, as we already pointed out, due to lack of experimental data, there is some freedom left to define the off-diagonal part of the unintegrated gluon density. Although it is not important for the total cross-section, it plays an important role for the azimuthal asymmetry.

Acknowledgments

We are grateful to Hans-Jürgen Pirner for many illuminating discussions. AHR would like also to thank Francois Gelis, Jamal Jalilian-Marian and Kirill Tuchin for useful discussions. This work was supported in part by Fondecyt (Chile) grants 1070517 and 1050589 and by DFG (Germany) grant PI182/3-1.

References

[1] PHENIX Collaboration, arXiv:0705.1711.

[2] PHENIX Collaboration, Phys. Rev .Lett. **96**, 032302 (2006).

[3] B. Z. Kopeliovich, H. J. Pirner, A. H. Rezaeian, Ivan Schmidt, Phys. Rev. **D77**, 034011 (2008)[arXiv:0711.3010].

[4] S. Turbide, C. Gale and R. J. Fries, Phys. Rev. Lett. **96**, 032303 (2006).

[5] S. Turbide, C. Gale, E. Frodermann, U. Heinz, Phys. Rev. **C77**, 024909 (2008) [arXiv:0712.0732].

[6] R. Chatterjee, E. S. Frodermann, U. W. Heinz, D. K. Srivastava, Phys .Rev. Lett. **96**, 202302 (2006).

[7] B.Z. Kopeliovich, A. Schaefer and A.V. Tarasov, Phys. Rev. **C59** (1999) 1609

[8] B. Z. Kopeliovich, Phys. Rev. C **68**, 044906 (2003).

[9] X. Ji, Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. **D55**, 7114 (1997). A. V. Radyushkin, Phys. Lett. **B380**, 417 (1996); Phys. Rev. **D56**, 5524 (1997).

[10] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. **D59**, 014017 (1999).

[11] B. Z. Kopeliovich, A. H. Rezaeian, H. J. Pirner and Ivan Schmidt, Phys. Lett. **B653**, 210 (2007).

[12] B. Z. Kopeliovich, J. Raufeisen and A. V. Tarasov, Phys. Rev. **C62**, 035204 (2000).

[13] A. H. Rezaeian, B. Z. Kopeliovich, H. J. Pirner and Ivan Schmidt, arXiv:0707.2040.

[14] S. Abreu *et al.*, arXiv:0711.0974.

[15] B. Z. Kopeliovich, J. Raufeisen, A. V. Tarasov, Phys. Lett. **B503**, 91 (2001).

[16] SMC Collaboration, Phys. Rev. **D58**, 112001 (1998).

[17] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969); C. W. De Jager, H. De Vries, C. De Vries, Atom. Data Nucl. Data Tables **36**, 496 (1987).

[18] E665 Collaboration, Z. Phys. **C67**, 403 (1995).

[19] STAR Collaboration, Phys. Rev. Lett. **89**, 202301 (2002).

[20] B. Z. Kopeliovich, A. H. Rezaeian, and Ivan Schmidt, under preparation.